Divine Garrett Model and Jupiter's Synchrotron Radiation

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Abstract.

Simulations of synchrotron emission from relativistic electrons trapped in Jupiter's magnetic field are used to evaluate the energetic electron distribution of the Divine-Garrett Jupiter radiation belt model at radial distances less than 4 Jovian radii. The fundamental characteristic of synchrotron emission, narrow beaming from gyrating electrons, provides the basis for constraints on both the magnetic field and the distribution of particles in Jupiter's inner magnetosphere. A comparison between model results and observations is presented. The results suggest the Divine Garrett model significantly underestimates the number of relativistic electrons (>1 MeV) present in Jupiter's inner magnetosphere. The results also indicate that the pitch angle distribution of relativistic electrons in the Jovian radiation belts is different than assumed in the Divine-Garrett model. These results have important implications for the development of self-consistent models of Jupiter's magnetosphere and the planning of future missions requiring close flybys of Jupiter.

Introduction

In the mid-1970's the Jet Propulsion Laboratory (JPL) began developing models of the Jovian environment to provide the National Aeronautics and Space Administration (NASA) with estimates of the high-energy electron, proton, and heavy ion fluxes. For the electrons and protons, which produce the cumulative radiation damage, this effort culminated in the Divine-Garrett model (D-G, Divine and Garrett 1983) and represents the sole tool to estimate the radiation dose for Jupiter flyby and orbiter missions.

The D-G model is a compact, quantitative model of the charged particles between 1 eV and several MeV based primarily on in-situ data returned from the Pioneer and Voyager flybys of Jupiter. The in-situ data were supplemented by Earth based radio telescope observations of the synchrotron emission and theoretical considerations. An important test of the reliability of the D-G model for energetic electrons in the inner Jovian magnetosphere is the ability to reproduce the observed pattern of synchrotron radiation. Divine and Garrett (1983) noted that the their electron distributions at L < 3 did not match the synchrotron observation and that the in-situ data their model was based on was insufficient to constrain model parameters at small L.

High levels of radiation pose a challenge to spacecraft design, with factors of uncertainty of two to four in the design environment having major consequences on the selection of survivable technologies. The above considerations have led a number of mission concepts to consider extremely close flybys or orbiters of Jupiter (to facilitate capture into orbit) in order to decrease propulsion mass requirements. While mission designers assume the required shielding increases as Jupiter orbit insertion distances decrease, analyzing the cost and risk of missions with close flybys is complicated by the relatively sparse data available on Jupiter's inner radiation belts.

The purpose of this paper is to use a new 3-D synchrotron emission model (Levin et al. 2000) to compare the D-G model with synchrotron emission observations. The new emission model allows a more in depth investigation of the high energy electron distribution including the spatial distribution (pitch angle and radial profile), spectral index and overall density. The goal of this study is to estimate the uncertainty of the energetic electron distribution in the D-G model and provide a basis for future work to determine whether detailed improvements are necessary.

While this paper focuses on relativistic electrons, we note that earlier work demonstrated a mismatch between decametric observations and the D-G model for low energy electrons in the inner Jovian magnetosphere. The observed (lack of) Faraday rotation (from Jupiter's radiation belts) and the existence of 100% elliptical polarization on the decametric emissions places an upper limit on the electron density in Jupiter's inner magnetosphere (excepting the ionosphere and Io torus). This upper limit is about 5 cm^{-3} (Warwick and Dulk, 1964; Parker, Dulk and Warwick, 1969; Lecacheux, 1988; Melrose and Dulk, 1991; Dulk, Lecacheux and Leblanc, 1992), which compares with 10-3000 cm^{-3} in the D-G model.

In this paper we use simulated observations to compare with single dish and interferometric maps of Jupiter's synchrotron emission at two frequencies (13 cm and 21 cm). Comparisons of beaming curves, spatial maps, and overall intensity are used to estimate inadequacies in the D-G energetic electron distributions. Experience in comparing simulated observations with previously developed electron distributions (Levin et al. 2000) are used to suggest modifications to the D-G model which may improve the model's fit to observation.

Background

At frequencies above about 100 MHz, electrons trapped in Jupiter's radiation belts generate a continuum of synchrotron emission. The Jovian decimetric emission is a combination of synchrotron radiation originating from relativistic electrons trapped in Jupiter's inner radiation belts and thermal emission from the planet's atmosphere. The synchrotron radiation component has been studied extensively and has indicated a long term variability (Klein et al., 1989). The combination of observations and theoretical analysis over the last few decades has led to an understanding of the physical details and characteristics of the synchrotron emission that are important for determining the physical description of Jupiter's inner radiation belts and magnetosphere. These characteristics are described in a number of reviews on the subject (e.g. Carr and Gulkis, 1969; Carr, Desch and Alexander, 1983).

Modeling and Observations

This study utilizes two types of radio telescope observations of synchrotron radiation. Single dish antennas measure the total flux density originating from the synchrotron emission region and arrayed antennas produce interferometric maps of the spatial distribution of the emission. Observation results are used to constrain input parameters in the synchrotron emission model (Levin et al. 2000). An iterative process is used to develop a static model of the radiation belts describing the energy spectrum, radial profile and pitch angle distributions of the high energy electrons. The sensitivity to errors in the magnetic field model are tested by producing simulated maps and beaming curves using both the O6 and VIP4 magnetic field models (Connerney, 1993) as described in Levin et al (2000).

Interferometric maps provide information on the spatial distribution of the emission. Combined with modeling results the observations demonstrate the importance of the magnetic field orientation to the relative intensity of the observed emission (Levin et al. 2000). VLA images at decimetric wavelengths (Figure 1) indicate the presence of radiating electrons at high magnetic latitudes as well as significant emission originating near the magnetic equator. For this reason, models of the Jovian synchrotron emission involve two distinct high energy electron distributions, a quasi-isotropic distribution responsible for the high latitude emission and a strongly pancake distribution representing electrons confined close to the magnetic equator (Roberts, 1976; Levin et al., 2000). Observations of the polarization and beaming of the emission are also consistent with a bi-modal electron pitch angle distribution. Previous theoretical studies of synchrotron radiation variability (de Pater and Goertz, 1990, 1994) have not included non-equatorial particles. These previous studies of diffusion theory cannot explain the maintenance of the quasi-isotropic population as suggested by the observations. Such characteristics and short term variability could be associated with changes in the pitch angle distribution of the trapped radiating electrons due to resonant scattering with whistler mode waves (Bolton, 1990). These waves could be stimulated either by electrical storms in the atmosphere (Lewis 1980) or triggered by natural instabilities induced by the anisotropic pancake distribution of trapped electrons (Sentman and Goertz, 1978).

Comparison with Divine Garrett

The synchrotron emission model can be used to constrain high energy electron distribution models of Jupiter’s inner magnetosphere. Using input derived from the Divine-Garrett radiation model the predicted synchrotron emission is calculated and compared with observation. Differences between the calculated emission and the observations can be due to errors in the magnetic field model and/or errors present in the electron distribution. The results of Levin et al. (2000) indicate the importance of the magnetic field, however, the results also suggest that both the VIP4 and O6 magnetic field models (Connerney, 1993) qualitatively capture the gross features of the field geometry in the radiation belts. Comparing simulated maps of the synchrotron emission from the D-G model and the electron distributions of Levin et al. (2000) using identical magnetic field models limits the source of errors to the electron distributions. The differences in overall emission intensity are directly proportional to errors in the assumed density of high energy electrons and the associated energy and pitch angle distribution of the electrons.

Figure 2 is the calculated synchrotron emission map using the Divine-Garrett model at 0 degrees CML. Comparison of the VLA and D-G map illustrate two important errors in the D-G model. The D-G model significantly underestimates the number of high energy electrons present in the inner Jovian magnetosphere, and the pitch angle and radial distribution of the electrons is different than represented in the D-G model. A more detailed discussion of these two points is offered below in the discussion section.

Discussion

Beaming Curve Comparison

The misalignment of Jupiter's magnetic field and spin axis causes Jupiter's magnetosphere to wobble as Jupiter rotates. The combination of non-dipolar terms in the Jovian magnetic field, the narrow beaming of the synchrotron emission (Jackson, 1975) and the distribution of synchrotron emitting electrons produce the observed variability in the intensity during a Jovian rotation. Beaming curves of Jupiter's synchrotron emission show the total intensity variations observed from Earth based telescopes during a single Jovian rotation (~10 hours). The relativistic beaming of the emission is sufficiently narrow to produce observable effects in the beaming curve as a function of DE, the declination of Earth as seen from Jupiter, which varies +/- 3.3 degrees during the Jovian year (Klein et al., 1989). An example of the beaming curve at DE = 0^o is shown in Figure 3 (top panel) as observed using the NASA/DSN antennas operating at 13 cm wavelength. The emission intensity is seen to vary approximately 10% during a single Jovian rotation. In contrast to the observed data, the center panel of Figure 3 shows the beaming curve as calculated from the D-G model. We discuss below how an error in the degree of anisotropy of the equatorial component of electrons can produce beaming curves similar to the D-G model.

The shape of the beaming curve is controlled by the pitch-angle distribution in Jupiter's inner radiation belts. The bottom panel of Figure 3 shows beaming curves simulated by modeling the equatorial electron pitch-angle distribution with two distinct functional forms; $\sin^1\alpha$ (solid blue) and $\sin^{10}\alpha$ (dashed red), respectively (the electron and magnetic field models used are identical otherwise). A decrease in the pitch-angle anisotropy leads to a dramatic flattening of the beaming curve. A highly anisotropic distribution ($\sin^q\alpha$, .with q>10) is required to reproduce the observed beaming curve and the equatorial component in the VLA maps (Figure 1). A less anisotropic distribution yields a smaller beaming effect and more emissivity in the high latitude lobes.

Map and Intensity Comparisons

The simulated synchrotron emission map (at 1400 MHz) calculated using the D-G model and the VIP4 magnetic field model (Connerney, 1993) is shown in Figure 2. This can be compared directly with the VLA map (from an identical geometry and observing frequency) shown in Figure 1. To compare the maps, we developed a simple "goodness of fit" statistic. The simulated map is smoothed to reflect the finite resolution of the VLA, and then subtracted from the VLA map to produce a residual map. We then calculate the variance of the residual map, summing the squares of all the (0.05 RJ by 0.05 RJ) pixels. The results indicate the D-G model is a factor of 3 worse than the model described in Levin et al. (2000).

The emission distribution of the D-G model maps differ dramatically from the observations indicating significant errors in both the electron distributions and densities. In addition to being significantly weaker in intensity, the high latitude lobes of the D-G model occur at higher L-shells (L~3.5 instead of L~2.4) and closer to the planet. The equatorial emission of the D-G model is more widely distributed in latitude and extends less in radial distance. The overall equatorial emission intensity is under represented in the D-G model by more than a factor of 5-10. The total map intensity of the D-G map is approximately 1.3 Jy as compared to 6.0 Jy in the observations. This suggests that the D-G model contains substantially fewer relativistic electrons (~1-50 MeV) than are actually present in Jupiter's inner radiation belts. In comparison, the simulated model map by Levin et al. (2000) is qualitatively similar to the VLA observations shown in Figure 1. The maps shown in Figure 1 and 2 indicate the synchrotron at 0 degree CML (central meridian longitude. VLA maps differ as a function of CML due to the same effects that cause the beaming curve (discussed above). We compared VLA maps with D-G model simulated maps for all CMLs and note that the D-G model consistently failed to match the emission distribution observed in the VLA maps.

The beaming curve, interferometric maps, and total intensity comparisons consistently indicate the D-G model underestimates the synchrotron radiation environment emanating from the region very close to Jupiter (< 4RJ). The synchrotron radiation characteristics are dependent on both the magnetic field and electron distributions. To identify errors in the electron distributions of the D-G model we compare models using identical magnetic field and electron energy spectral index. Errors associated with the electron energy spectrum will be common to all simulations. We further investigated the sensitivity to errors in the energy spectrum by reproducing maps and beaming curves for a variety of energy distributions (including distributions similar to those described by Divine-Garrett (1983) and Mihalov et al. (1998)). All results indicate errors in the D-G model.

Figure 4 is a difference map between the D-G model of Figure 2 and the VLA data of Figure 1. The difference map is calculated by subtracting the D-G model from the VLA data. The results indicate that the D-G model underestimates the total overall emission intensity by a factor of 6 and underestimates emission in specific regions by factors as high as 50. At the equator near R=1.4 RJ, the error is approximately a factor of 20. As can also be seen in Figure 4, portions of the high latitude regions near Jupiter are overestimated by the D-G model, largely due to the incorrect location of the high latitude lobes in the D-G model. The D-G model places the high latitude peaks at higher latitudes than observed. A detailed analysis is necessary to estimate the error in the D-G model for specific locations in Jupiter's inner radiation belts. We plan to develop a more detailed model in the future as discussed below.

Jupiter's synchrotron radiation exhibits temporal variability on time scales of weeks to years (Klein et al. 1989, Bolton et al. 1989). The differences evident from the comparison of simulated maps using the D-G model, the simulated maps of Levin et al. model and the VLA observations are much greater than expected from the modest variability observed over the last few decades. Furthermore, no interferometric maps have ever shown spatial or intensity characteristics similar to the D-G model simulations presented in this study (de Pater and Jaffe 1984, Dulk et al 1999ab).

Conclusions and Future Work

Our results indicate that the Divine-Garrett model does not accurately describe the high energy (>1 MeV) electron population present in Jupiter's inner radiation belts (< 4 RJ) and that substantial modifications to the model are required. Simulated synchrotron emission maps generated with the Divine-Garrett model do not reflect the basic characteristics of the Jovian synchrotron emission such as the total flux density, spatial distribution, polarization and variability with Jupiter rotation. Current observations are sufficient to improve the model, however, further work is required to constrain the electron distribution energy spectrum and detailed radial profile. Results from the Galileo probe data suggest the energy spectrum may be different for the equatorial (pancake) and high latitude (less anisotropic) components (Mihalov et al. 1998). If the energy spectrum of either component is softer than assumed by Divine and Garrett, the results reported here represent a minimum error in the D-G model.

The difference between synchrotron emission observation and the D-G model varies spatially as shown in Figure 4. In most regions, the D-G model underestimates the radiation environment (electron number density) by a factor of 5 - 20. However, in small regions, the error increases substantially and in a few select regions the D-G model overestimates the radiation. With careful analysis, a spacecraft trajectory could be designed to minimize the effects of these errors. Our results indicate the region of maximum error (underestimation) is close to the planet (< 2 RJ) at the equator and near latitudes 55-75 degrees. This can be seen from the peak differences in Figure 4.

We anticipate currently planned observations in the near future with the Cassini spacecraft in January 2001 will provide new information on the energy spectrum by revealing the spatial distribution of synchrotron emission at very high frequencies (corresponding to mean electron energies > 40 MeV). Further modeling using the Salammbo code (Beutier and Bosher, 1995) should also place new constraints on the high energy electron distributions and processes governing the distributions present in the inner radiation belts of Jupiter.

Figures

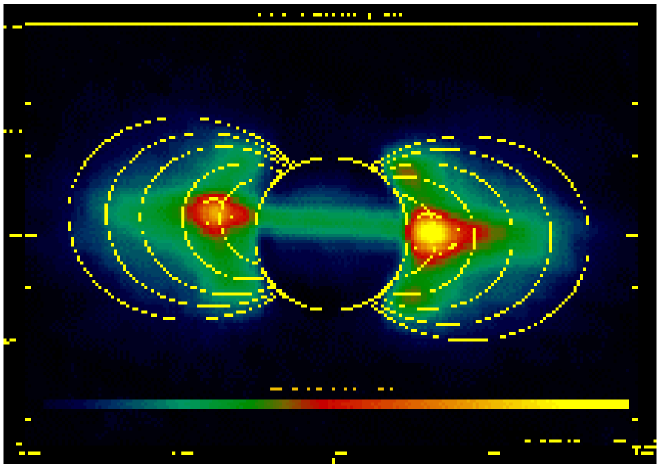

Figure 1. VLA map at 21 cm (1400 MHz) at 0 degrees CML and De=0. Thermal emission has been subtracted and outline of Jupiter disk and O6 magnetic field lines shown for reference.

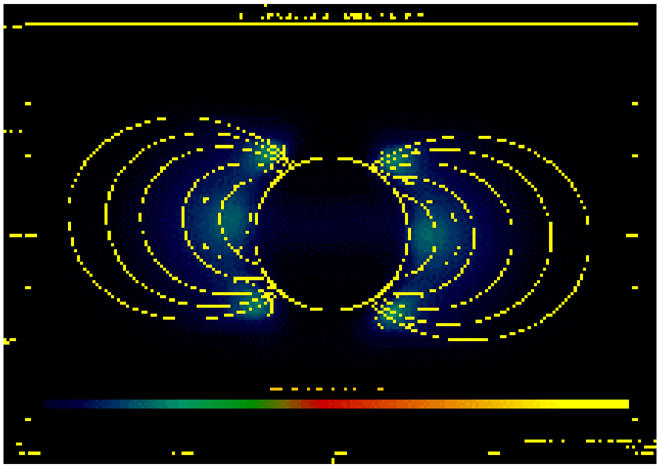

Figure 2. D-G model map at 1400MHz (21 cm) at 0 deg CML and DE=0, Color scale identical to VLA observation shown in Figure 1.

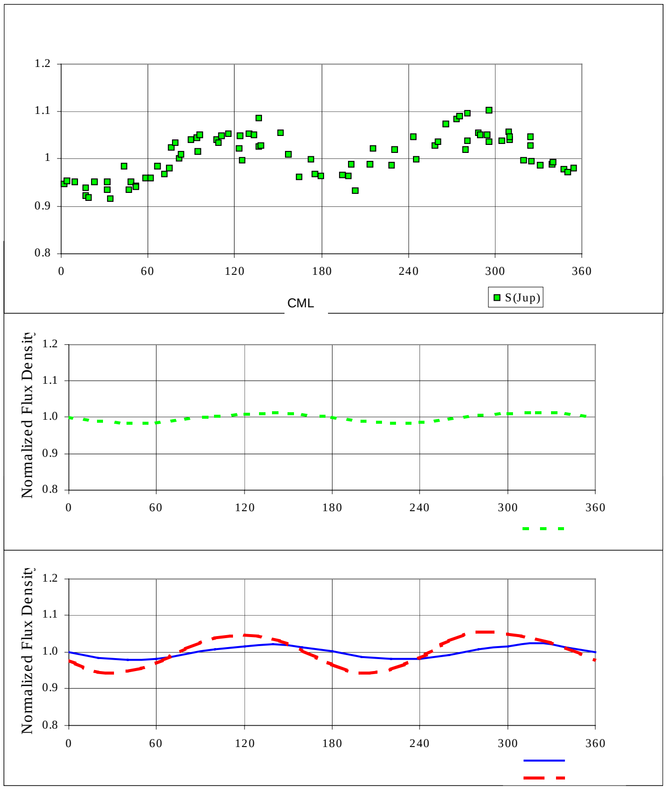

Figure 3. Comparison of beaming curves. Top panel shows DSN observations of the beaming curve. Middle panel shows a beaming curve calculated from the D-G model distribution (note the flatter curve). Bottom panel shows two simulated beaming curves calculated with q~10 (dotted line, $f(\alpha)$ $\sin^{10}$ more anisotropic distribution) with q~1 (solid line, $f(\alpha)$ $\sin^{1}$ more isotropic distribution). All curves are for 13 cm wavelength observations at De=0.

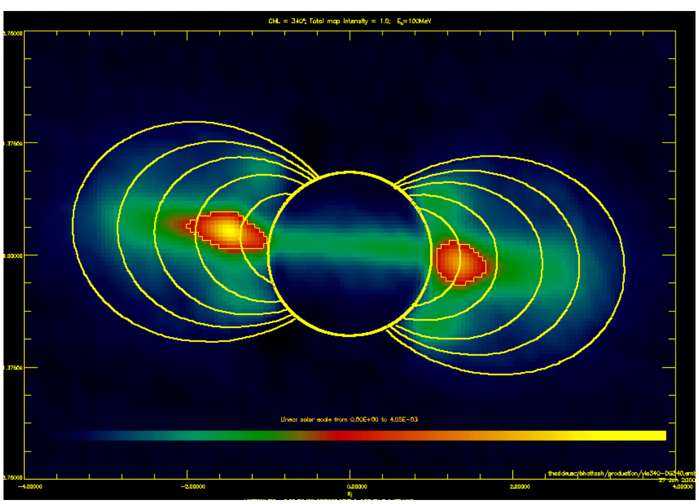

Figure 4. Difference map of VLA minus the DG model simulation for 340 degrees CML. The color scale is identical to Figure 1 and 2. This map looks very similar to Figure 1 indicating the serious underestimate of synchrotron emission produced by the D-G model.

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